NUMERICAL SIMULATION OF A HYDROGEN COMBUSTION IN A BOUNDARY LAYER WITH A DIFFERENT BLOWING PARAMETERS

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1. Introduction

The interest to study of boundary layers with blowing of reacting chemical substances is due to extensive applications of this process. The mechanism of how the porous blowing effects heat and mass transfer and friction was studied deeply for nonreactive flows [1, 2], but combustion makes the whole pattern more complex. The heat release in the reaction zone creates a strong effect, which changes significantly the thermophysical properties and, consequently, turbulence characteristics. This was proved by existing experimental data on turbulent structure and heat and mass transfer in near-wall turbulent pulsations in the near-wall diffusive flame [3-7].

A certain progress has been achieved in description of this problem, and simulation of turbulent combustion in a boundary layer [8, 9] gives analysis of different models of chemical reactions [10].

However, this problem creates many questions that still require a more detail study. One of the issue is how the intensity of fuel blowing through a porous surface affects the structure of the boundary layer, position of flame front, heat and mass transfer, and friction.

The current paper presents results of simulation for a turbulent flow with hydrogen blowing into the boundary layer. Since the process has many parameters, the main emphasis was put on analysis of dynamic parameters – velocity profiles, integral scales and surface friction.

2. Problem statement and main equations

A plain porous plate for supply of pure hydrogen is exposed to a non-gradient airflow with velocity u_0 = 20 m/s. The hydrogen fed through the wall reacts with air oxygen inside the boundary layer, at the combustion front, and reaction products diffuse toward the external limit of the boundary layer and toward the wall. To exclude the temperature factor, all calculations were performed at a fixed length and the same temperature for the wall and stream core $T_0 = T_w$ = 300 K. The concentration of the blown hydrogen was taken as a constant over the length $\left(C_{H_2}\right)_w = const$. Correspondingly, the mass flux over the plate length decreased with a growth of the boundary layer thickness.

The intensity of hydrogen feed was varied through a change of hydrogen concentration on the wall. Our simulation was performed for a most wide range of concentrations $\left(C_{H_2}\right)_w = 0{,}02 - 0{,}8$. At a lower concentration, there was no flame at all, and we failed to obtain a stable solution at higher concentrations of hydrogen. This range of concentration corresponds to a wide range of the blow parameter $b_1 = 2 j_w / \rho_0 u_0 c_f \cong 0{,}1 \div 4$.

This work uses k-ε model of turbulence (LRN – modification by Chien [12]). The equation for each variable can be presented in the generalized form:

$$\frac{\partial \rho U \Phi}{\partial x} + \frac{\partial \rho V \Phi}{\partial y} = \frac{\partial}{\partial y}\left(\Gamma_\Phi \frac{\partial \Phi}{\partial y}\right) + S_\Phi \qquad (1)$$

Report Documentation Page

Report Date	Report Type	Dates Covered (from... to)
23 Aug 2002	N/A	-

Title and Subtitle Numerical Simulation of a Hydrogen Combustion in A Boundary Layer With A Different Blowing Parameters	**Contract Number**
	Grant Number
	Program Element Number
Author(s)	**Project Number**
	Task Number
	Work Unit Number
Performing Organization Name(s) and Address(es) Institute of Theoretical and Applied Mechanics Institutskaya 4/1 Novosibirsk 530090 Russia	**Performing Organization Report Number**
Sponsoring/Monitoring Agency Name(s) and Address(es) EOARD PSC 802 Box 14 FPO 09499-0014	**Sponsor/Monitor's Acronym(s)**
	Sponsor/Monitor's Report Number(s)

Distribution/Availability Statement
Approved for public release, distribution unlimited

Supplementary Notes
See also ADM001433, Conference held International Conference on Methods of Aerophysical Research (11th) Held in Novosibirsk, Russia on 1-7 Jul 2002

Abstract

Subject Terms

Report Classification unclassified	**Classification of this page** unclassified
Classification of Abstract unclassified	**Limitation of Abstract** UU

Number of Pages
6

Variables Φ, diffusion coefficients Γ_Φ, and source terms Γ_Φ are presented in the table.

U	$\mu + \mu_T$	0
1	0	0
k	$\mu + \mu_T$	$\mu_T \left(\frac{\partial U}{\partial y} \right)^2 - \rho\varepsilon$
ε	$\mu + \mu_T$ /1.3	$\left[c_1 f_1 \mu_T \left(\frac{\partial U}{\partial y} \right)^2 - \rho c_2 f_2 \tilde{\varepsilon} \right] \frac{\tilde{\varepsilon}}{k} - 2\mu \frac{\tilde{\varepsilon}}{y^2} e^{-0,5^+}$
H	$\mu / \mathrm{Pr} + \mu_T / \mathrm{Pr_T}$	$\sum_{j=1}^{nsp} (Le_j - 1) H_j \frac{\partial c_j}{\partial y}$
c_i	$\mu / \mathrm{Sc}_i + \mu_T / \mathrm{Sc_T}$	$\dot{w}_i$

Here U – longitudinal velocity, H – enthalpy of the mixture, c_i – mass fraction of i-th component, k – kinetic energy of turbulence and ε - dissipation rate of turbulence. Turbulence model constants and functions were taken from [12].

The parameters in these equations like viscosity, Prandtl number, Schmidt number were calculated by semiempirical formulas for a multicomponent gas mixture [11], and the density was calculated from the ideal gas law.

As preliminary calculations demonstrated, combustion under these conditions is determined mainly by the rate of reactants mixing, since the reaction rate is rather high. Therefore we imply in further calculations that only the reaction *fuel+oxidizer→products* takes place, and its rate is infinitely high. This corresponds to the so-called diffusion model of combustion.

Under these assumptions the Lewis number is different from one (Le ≠ 1) and, according to data from [10], this approximation gives a good agreement with experiment and the combustion under these conditions can be considered as a chemical equilibrium process.

The values of turbulent numbers of Prandtl and Schmidt were taken constant over the boundary layer thickness and equal to 0,9.

The boundary conditions for this problem were the following:

— on the initial cross-section (x = 0)

$k = k_0$; $\varepsilon = \varepsilon_0$; $u = u_0$; $V = V_0$; $T = T_0$;

— on the external side of the boundary layer ($y = \delta$)

$u = u_0$; $T = T_0$; $C_{O_2} = 0.23$; $C_{N_2} = 0{,}77$ and $\partial\Phi/\partial y$ for other variables;

— on the wall (y = 0)

$$u = 0;\ k = 0;\ \varepsilon = 0;\ C_{H_2} = (C_{H_2})_w;\ T = T_w;\ (j_w)_{H_2} = \frac{\rho D}{1 - (C_{H_2})_w} \left(\frac{\partial C_{H_2}}{\partial y} \right)_w .$$

The advantage of the used turbulence model is that it works at low Reynolds numbers. Therefore it was possible to calculate the flow even for laminar range. This work uses coordinate transformation and numerical method for solving boundary layer equations that have been proposed by Denny et. al. [13].

Before the simulation, we performed some test runs, for checking of operability of numerical algorithm and turbulence model. The friction and heat transfer on a impenetrable plate were calculated for blow of the same (or foreign) gas. Calculations demonstrated a good correspondence with the laws for friction and heat and mass transfer known from literature [1, 2].

3. Simulation results and discussion

The friction coefficient as a function of Reynolds number Re_x with hydrogen blow and combustion in the boundary layer is plotted in Fig. 1. Here the curves for different hydrogen concentrations on the wall are presented, and, correspondingly, data for different intensity of blow.

Let us consider the behavior of the friction. With an increase in the wall concentration and blow intensity, the friction decreases. However, unlike for nonreactive flows, combustion creates a lag in laminar-turbulent transition: for a low intensity of blow it occurs at Reynolds numbers $Re_x = (3\div5)10^6$, at this is by one order higher than for the no-friction situation. For a higher intensity of blow, the transition shifts to the zone of smaller Reynolds numbers.

Existence of intensive heat release in a boundary layer influences the distribution of friction over the plate length. As analysis revealed, for laminar zone of flow the exponent in the friction law is different from 0.5; for turbulent regime the blow creates variation in the exponent in the limits $n = 0\div0{,}16$.

The profiles of velocity, total enthalpy, and generalized concentration are almost coincide between them, and this tell us about similarity for processes of heat and mass transfer and friction even under such complicated conditions. The prove that Reynolds analogy is valid for reacting flows (with the mentioned variables) was provided also experimentally [3].

Evolution of velocity profiles over the length of porous plate under combustion condition is demonstrated in Fig. 2. Here the velocities are represented in traditional semi-logarithmic coordinates. Here $u^+ = u/u_\tau$; $u_\tau = \sqrt{\tau_w/\rho_w}$; $y^+ = yu_\tau/\nu$.

For Reynolds number $Re_x \le 10^6$, the velocity profile has no the traditional intrinsic zone with a logarithmic law. This manifests that the flow mode is close to laminar; this is caused by a strong heat release in the boundary layer. With a higher Reynolds, the profile deviates from the laminar distribution, so the flow becomes turbulent. These tendencies were noted in Fig. 1 also.

The effect of blow intensity on velocity profile in a boundary layer is shown in Fig. 3 in semi- logarithmic coordinates.

In this graph, the simulation results with/without combustion are compared directly (all other external parameters are identical). At low wall concentrations (Fig. 3a – small blowing) the velocity profile is close to the standard distribution in a laminar sublayer and at the intrinsic logarithmic zone. With combustion, the profile undergoes a considerable change. As it was for low Reynolds number, we have no any logarithmic zone: this testifies that the influence of heat release on the flow structure is overwhelming.

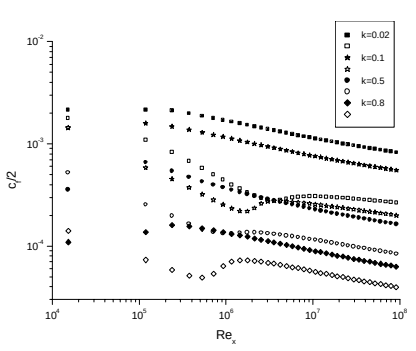

Fig. 1. Friction coefficient in a boundary layer with hydrogen injection and combustion (hollow symbols – combustion, solid – injection without combustion).

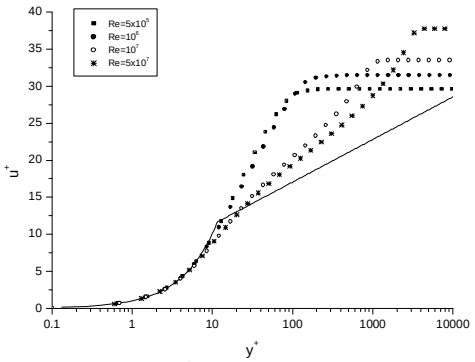

Fig. 2. Velocity profiles (combustion case, C_{H2}=0.5) dependence on Reynolds number. Solid lines are standard turbulent velocity profile $u^+ = y^+$, *if* $y^+ < 11$, $u^+ = 5.75\lg y^+ + 5.5$ elsewhere.

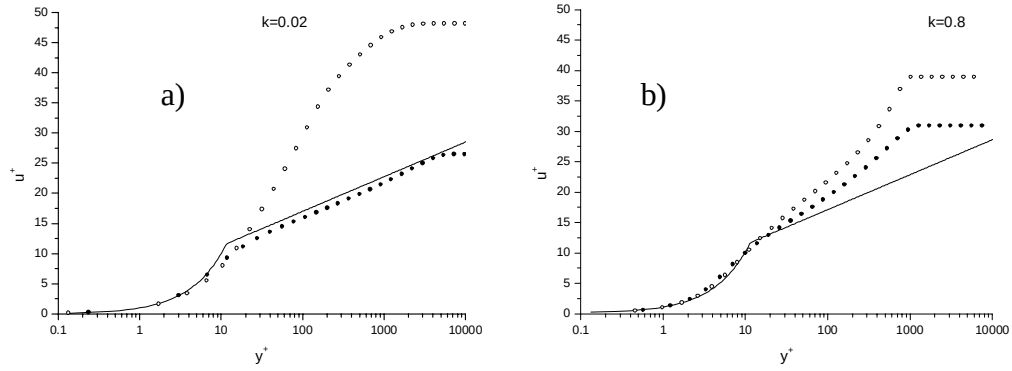

Fig. 3. Velocity profiles in a boundary layer with injection and combustion (hollow symbols – combustion, solid – injection without combustion). $Re_x = 10^7$

The existence of flame front makes the profiles closer even at high rates of blowing. We can see in Fig. 3b that this difference became minimal, but the velocity profile (no combustion) display a tendency of deviation from the classical logarithmic distribution.

There is a strong effect of heat release on flow structure at the flame front. Depending on the blow intensity, the front coordinate may shift within the boundary layer thickness. This is illustrated by data presented in Fig. 4. With a higher intensity of blow, the front coordinate moves out from the wall, and this shift may be considerable. Obviously, the fact where the flame front is – in the near-wall or external zone, must influence the transfer characteristics.

All of these peculiarities of flow structure in a boundary layer with combustion can be applied to the behavior of the friction ratio. The dependency of this coefficient on blow parameter is shown in Fig. 5. Here C_f/C_{f0} is the friction function, C_{f0} is the friction for a impenetrable isothermal plate, and $b_1 = 2 j_w / \rho_0 u_0 c_f$ is the blow parameter. From data in Fig. 5 we can estimate the contribution of blow and combustion into reduction of friction. The influence of every of these factors reduces the friction, and this effect is considerable. With the joint action of both factors, the reduction in friction may reach a high value. However, for intensive blow, the results of simulation for flows with and without reaction become closer and the effect from combustion is weaker because the flame front is pushed out from the wall and from the outer side of the boundary layer.

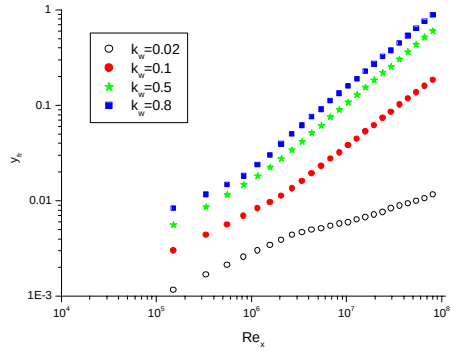

Fig. 4. Flame front position dependence on blowing .

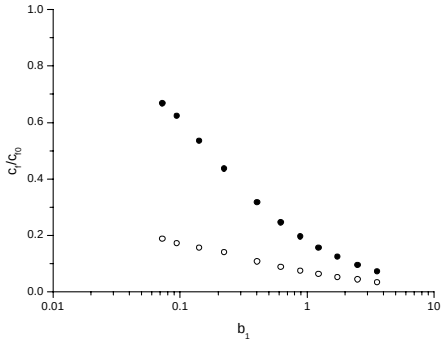

Fig. 5. C_f/C_{f0} dependence on blowing parameter (hollow symbols – combustion, solid – injection without combustion). $Re_x = 10$

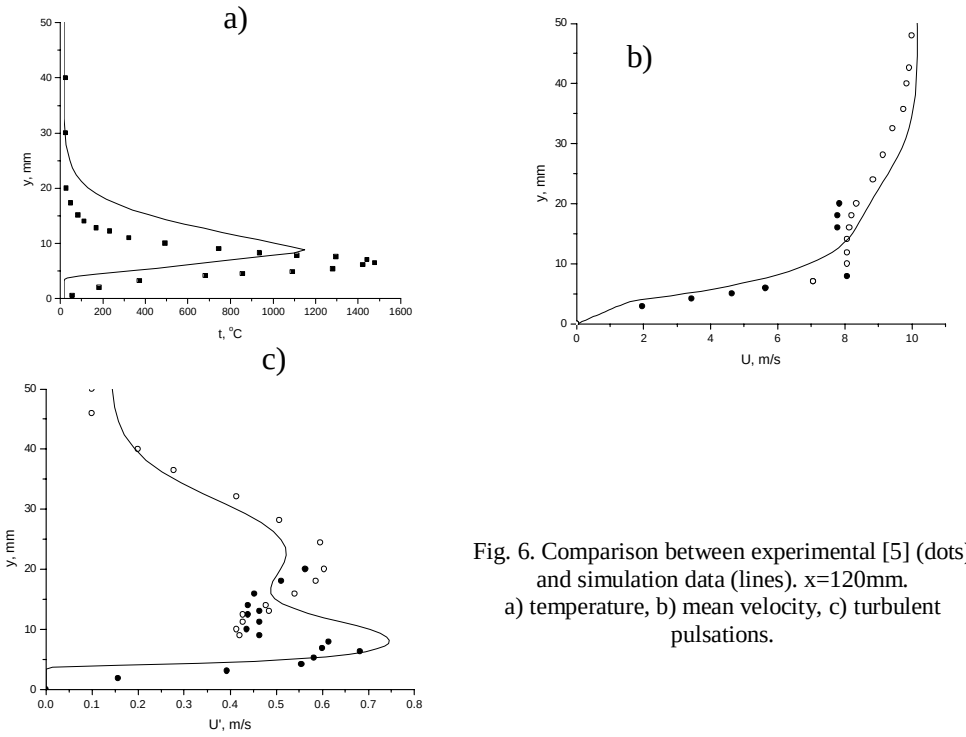

Fig. 6. Comparison between experimental [5] (dots) and simulation data (lines). x=120mm.
a) temperature, b) mean velocity, c) turbulent pulsations.

While comparing our simulation results with experimental data on hydrogen combustion [5] (which are qualitatively similar), we faced the problem described in [14]. The matter is that those experiments were conducted at high blow parameters and we failed to obtain a steady solution for this level of regime parameters $\left(j_w / \rho_0 u_0 \approx 0{,}01\right)$. A similar problem was discovered in paper [14], and calculation was possible only with use of the model of mixing length.

In order to compare the results with experimental data solution of incompressible gas dynamics equations were performed without boundary layer approximation. Boundary conditions were taken from experimental data described in [5]. Simulation and experimental results are shown in Fig. 6. From Fig. 6a we can see that simulation gives correct results on the flame position while temperature in the flame front is 20% lower than in the experiment. Fig. 6b and Fig. 6c show good agreement between simulation and experimental data on mean longitudinal velocity and its pulsation.

REFERENCES

1. **Kutateladze S.S., Leontiev A.I.** Heat and mass transfer and friction in a turbulent boundary layer, Moscow: Energia, 1972 (in Russian).
2. **Eroshenko V.M., Zaichik L.I.** Hydrodynamics and heat and mass transfer on a porous surface. Moscow: Nauka, 1984 (in Russian).
3. **Kulgein N.G.**, Transport processes in a combustible turbulent boundary layers // J. Fluid Mech. 1962. Vol. 12. P. 417-437.
4. **Woolridge C.E., Muzzy R.J.** Measurements turbulent boundary layer with porous wall injection and combustion: Proc. Tenth Symp. (Intern.) on Combustion. New York: Academic Press, 1965, P. 1351-1362.

5. **Ueda T., Mizomoto M., Ikai S.** Thermal structure of a flat plate turbulent boundary layer diffusion flame // Bul. JSME. 1983. 26. P. 399-405.
6. **Boyarshinov B.F., Volchkov E.P., Terekhov V.I.** Structure of a boundary layer with ethanol injection and combustion // Phis. Gor. Vzryva. 1992. 3. P. 29-36 (in Russian).
7. **Boyarshinov B.F., Volchkov E.P., Terekhov V.I.** Heat and mass transfer in a boundary layer with ethanol evaporation and combustion // Phis. Gor. Vzryva. 1994. 1. P. 8-15 (in Russian).
8. **Oka S., Sijercic M., Stefanovic P., Nemoda S., Zivkovic G**. Mathematical modeling of complex turbulent flows // Rus. J. Eng. Thermophysics. 1994. Vol. 4, No. 3. P. 245-284.
9. **Volchkov E.P., Dvornikov N.A., Perepechko L.N.** Mathematical modeling of hydrogen turbulent combustion in a boundary layer // IPJ. 1998. Vol. 71, No. 1. P. 86-91 (in Russian).
10. **Volchkov E.P., Dvornikov N.A., Perepechko L.N.** Comparative study of different models for turbulent boundary layer combustion // Phis. Gor. Vzryva. 1996. Vol. 32, No.4. P. 37-42 (in Russian).
11. **Reid R.C., Prausnitz J.M., Sherwood T.K.** The properties of gases and liquids. / Third edition. New York: McGraw, 1980. 482 p.
12. **Chien K.-Y.** Prediction of channel and boundary layer flows with low-Reynolds-number turbulence model // AIAA J. 1982. Vol. 20. P. 33-38.
13. **Denny V.E., Landis B.R.** An improved transformation of the Patankar – Spolding type for numerical solution of two-dimensional boundary layer flows // Int. J. Heat Mass Transfer. 1971. Vol. 14. P. 1859-1862.
14. **Jones J.W., Isaakson L.K., Vreeke S.** A turbulent boundary layer with mass addiction, combustion, and pressure gradient // AIAA J. 1971. Vol. 9.